MYCOTAXON

ISSN (print) 0093-4666 (online) 2154-8889 Mycotaxon, Ltd. ©2022

July–September 2022—Volume 137, pp. 495–520

https://doi.org/10.5248/137.495

Mucor septatiphorus nom. nov. and other *Mucor* species recorded from the Brazilian upland forest

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Abstract—During a survey of mucoralean diversity in three different fragments of upland forest located in the semi-arid region of Pernambuco, Brazil, 14 species of *Mucor* were recorded; twelve of them reported for the first time from upland forest areas. We propose a replacement name for *Mucor septatus* nom. illeg. and present detailed descriptions and illustrations of the specimens isolated.

Key words—*Mucoraceae*, *Mucoromycota*, soil, taxonomy, zygosporic fungi

Introduction

The semi-arid region of Brazil has broad phytophysiognomic heterogeneity. The forest formations in these regions comprise the upland forests, or 'Brejos Nordestinos,' which are fragments of humid forests surrounded by caatinga vegetation, a predominant vegetation type in the Brazilian semiarid region (Tabarelli & Santos 2004). These areas are refuges for organisms within the semi-arid domain and are associated with the occurrence of plateaus that confer mild climatic conditions and higher vegetation cover to the region, compared to the surrounded semi-arid ecosystems (Medeiros & Cestaro 2019).

Unfortunately, the Brazilian upland forests have undergone a continuous and systematic process of environmental degradation due to the unsustainable and intense consumption of their environmental assets (Medeiros & Cestaro 2019). These factors compromise the quality of the original ecosystems and cause serious erosion processes, leading to a huge loss of biodiversity (Freire & al. 2018).

Studies have reported the high diversity of *Mucoromycota* Doweld in different Brazilian ecosystems (Lima & al. 2016, 2018b, Souza & al. 2018, Flora e Funga do Brasil 2022); nevertheless, data are still scarce on fungal communities as well as the ecological relationships of these microorganisms with substrates and with other organisms in these ecosystems. Only 37 species of this phylum (including three *Mucor* spp.: *M. souzae*, Crous & al. 2018; *M. septatum* [nom. illeg.], Souza & al. 2018; and *M. pernambucoensis*, Lima & al. 2018c) have been reported from the Brazilian upland forest, but this probably does not reflect the true richness of *Mucoromycota* in these ecosystems.

Mucor Fresen. is the most representative genus in terms of number of species in *Mucoromycota*, and Wijayawardene & al. (2022) estimated around 98 valid species for this genus. *Mucor* species are characterized by the production of non-apophysed sporangia on simple or branched sporangiophores that arise directly from the substrate, while basal rhizoids and stolons are not produced (Benny & al. 2014). Species of *Mucor* may occur as heterothallic (majority) or homothallic forms, and zygospores have almost equal opposite suspension cells without appendages (Hoffmann & al. 2013). Although most *Mucor* representatives are saprobic, some have been reported as opportunistic pathogens causing deep, systemic, and cutaneous mycoses in humans, such as *M. circinelloides*, *M. indicus*, *M. irregularis*, *M. racemosus* Fresen., and *M. ramosissimus* Samouts. (Álvarez & al. 2011, Hoffmann & al. 2013). Voglmayr & Clémençon (2016) described *M. lilianae* Voglmayr & Clémençon and *M. rudolphii* Voglmayr & Clémençon as endoparasites of hypogeous *Hysterangium* basidiomes based on SSU, ITS, and LSU (rDNA)sequences and zygospore morphology, thus expanding the knowledge on the ecological niches of the genus. Several *Mucor* taxa are utilized in biotechnological processes due to their capacity to produce enzymes and organic acids (Kosa & al. 2018).

In view of the ecological and biotechnological importance of *Mucoromycota* and motivated by the constant process of degradation of the Brazilian upland forests, we assessed the *Mucor* communities in soils from upland forests in

the semi-arid region of Pernambuco State to expand the knowledge on the geographical distribution of these fungi. We also describe and illustrate the specimens isolated.

Materials & methods

Study site and soil sampling

The soils were sampled monthly in three upland forest areas in the semi-arid region of Pernambuco, Brazil, during July–December 2016: Brejo da Serra do Bituri (Brejo da Madre de Deus municipality), Brejo de Taquaritinga do Norte (Taquaritinga do Norte municipality), and Brejo do Sítio Carro Quebrado (Triunfo municipality). The samples were placed in plastic bags, kept in polystyrene boxes with ice, and taken to the laboratory.

Isolation, purification, and identification of *Mucor* species

Five milligrams of soil were sprinkled on the surface of wheat germ agar culture medium (Benny 2008) plus chloramphenicol (80 $mg.L^{-1}$) in Petri dishes, performed in triplicate. The Petri dishes were stored for 72 h (28 ± 2°C) under alternating 12 h periods of light and dark. For purification, fragments of colonies were transferred separately to Petri dishes with malt extract agar (Benny 2008) plus chloramphenicol (80 $mg.L^{-1}$). Fragments of selected fertile areas of colonies removed from the Petri dishes for analyses of fungal structures were placed (along with a drop of 3% KOH) onto microscope slides and observed under Zeiss Axioscope 40 light microscope. Seventy measurements were made for each fungal structure. The *Mucor* taxa were identified by analyzing macroscopic (colony color, appearance, diameter) and microscopic (microstructures) characters, as described by in the literature (Schipper 1973, 1975, 1976, 1978; Pei 2000; Madden & al. 2012; Li & al. 2016; Crous & al. 2018; Souza & al. 2018; Lima & al. 2017; Wagner & al. 2019). Living cultures of isolated *Mucor* spp. are deposited at the URM culture collection, Universidade Federal de Pernambuco, Recife, Brazil (URM).

Data of distribution and habitat

Information on the distribution and habitat of *Mucor* spp. was obtained from scientific manuscripts, culture collection vouchers, the Global Biodiversity Information Facility GBIF (https://www.gbif.org), GenBank (https://www.ncbi.nlm.nih.gov/genbank), Flora e Funga do Brasil (http://floradobrasil.jbrj.gov.br), and the plutoF platform (https://plutof.ut.ee).

Culture isolation results

We isolated 14 *Mucor* species: *M. circinatus*, *M. circinelloides*, *M. griseocyanus*, *M. guilliermondii*, *M. hiemalis*, *M. inaequisporus*, *M. indicus*, *M. irregularis*, *M. jansseni*, *M. lusitanicus*, *M. luteus*, *M. septatus* [nom. illeg., renamed below], *M. souzae*, and *M. variicolumellatus*.

Taxonomy

Mucor circinatus D.X. Lima, G. Walther & A.L. Santiago,
Phytotaxa 329(3): 271 (2017) Fig. 1A–D

Colony initially white becoming yellowish brown, reverse cream, colonizing the entire Petri dish (9 cm diam., 0.5 cm high) in 4 days at 25°C on malt extract agar (MEA). Sporangiophores hyaline to slightly light gray, with slightly rough walls, sympodially branched, 2.5–18 µm diam., recurved, growing directly from the substrate, circinate, often arising in the curvature of the previous branch next to the septum. Sporangia light yellow then becoming brown, globose (16–)20–35(–55) µm diam., smooth-walled, wall persistent. Columellae hyaline, globose to applanate (12–)17.5 × 30(–45) µm diam., smooth-walled. Sporangiospores hyaline, angular, 4 × 6.5(–7.5) µm, smooth-walled. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, soil samples, 1056 m a.s.l., soil samples, 5.XI.2016, C.A.F. Souza (URM 7774).

Habitat—Different soil types (Zycha 1935, Peries & al. 1979, Souza & al. 2011, Lima & al. 2017).

Geographic distribution—Australia, Brazil, Colombia, Malaysia, South Africa, Sri Lanka, Taiwan.

Comments—The morphological characteristics of URM 7774 (e.g., circinate sporangiophores ≤18 µm diam.; angular sporangiospores mostly 4 × 6.5 µm) correspond well to those described by Lima & al. (2017). This is the first report of *M. circinatus* in the Brazilian upland forest.

Mucor circinelloides Tiegh.,
Ann. Sci. Nat., Bot., sér. 6, 1: 94 (1875) Fig. 1E–H

Colony initially yellowish white, becoming yellowish gray to brownish, reverse yellow, colonizing the entire Petri dish (9 cm diam., ≤1 cm high) in 5 days at 25°C, on MEA. Sporangiophores hyaline to light gray, some with yellowish content, slightly encrusted-walled, repeatedly sympodially branched, with long and short branches, erect or slightly recurved; short sporangiophores more profusely branched with short and often circinate branches, ≤18 µm diam. Sporangia initially yellowish becoming brownish grey at maturity, globose, 35–85(–90) µm diam., with smooth and slightly incrusted wall. The wall of larger sporangia is deliquescent, persistent in the smallest ones. Columellae hyaline to brownish grey, globose, 10–35 µm diam., obovoid to slightly ellipsoidal, 20–60(–65) × 20–45 µm, smooth-walled,

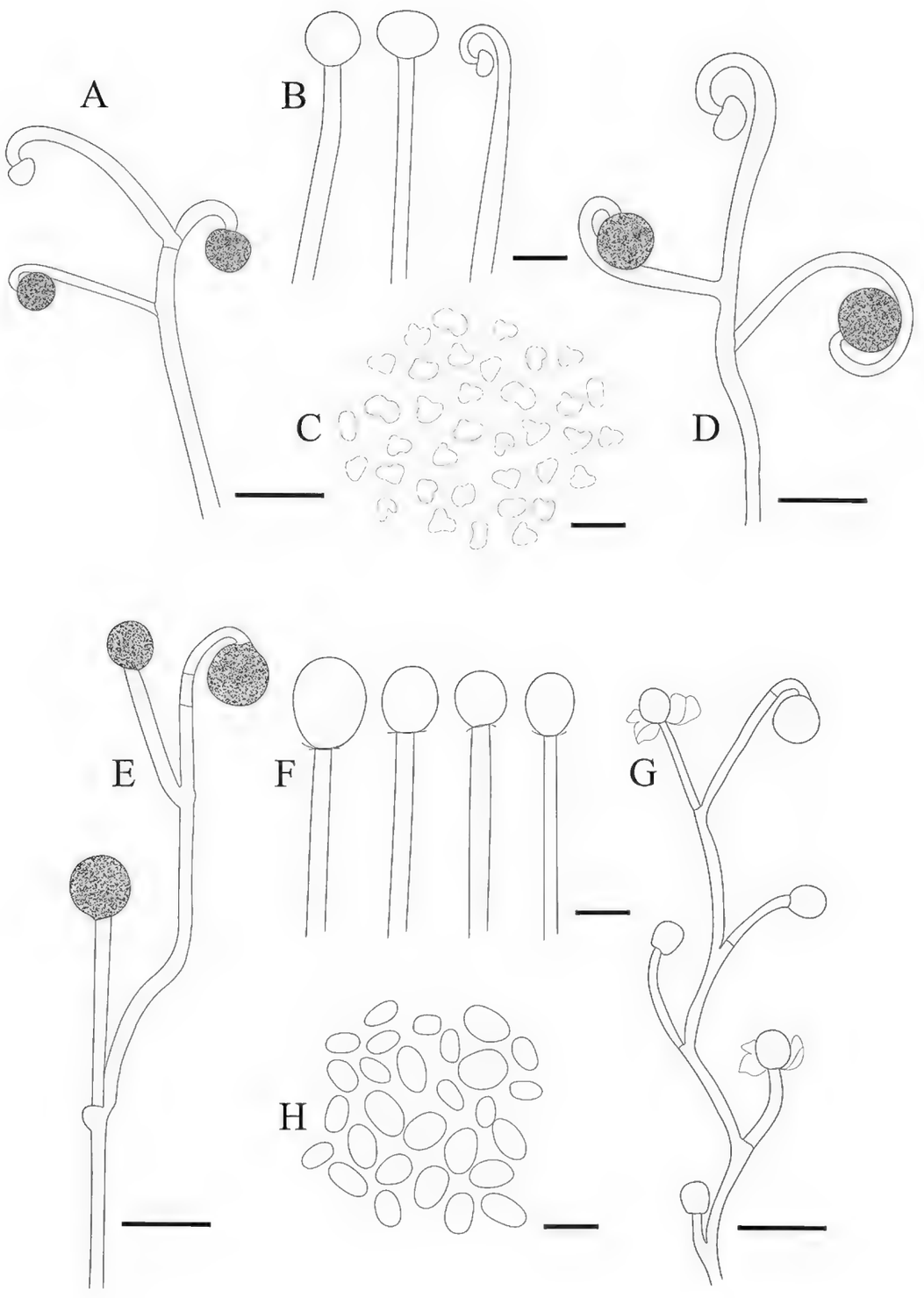

FIG. 1. ***Mucor circinatus*** (URM 7774): A. Branched circinate sporangiophores with sporangia and columella; B. Unbranched sporangiophores with columellae; C. Angular sporangiospores; D. Branched circinate sporangiophore with sporangia and columella; ***Mucor circinelloides*** (URM 7770): E. Branched sporangiophore with sporangia; F. Unbranched sporangiophores with columellae; G. Repeatedly sympodially branched sporangiophore with sporangium and columellae; H. Ellipsoid sporangiospores. Scale bars = 20 μm.

collar common. Sporangiospores hyaline, ellipsoid 4–9 × 3.5–6.5 µm, smooth-walled. Zygosporangia not observed.

Specimen Examined—**BRAZIL, Pernambuco, Brejo da Madre de Deus**, Brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 9.VII.2016, C.A.F. Souza (URM 7770).

Habitat—Different soil types (Schipper 1976, Domsch & al. 1980, Mousavi & al. 2018), cattle, goat, and sheep dung (Souza & al. 2017), plants including fruits, such as *Capsicum annuum* and *Triticum aestivum* (Walther & al. 2013), yogurt (Snyder & al. 2016), commercial honey, fermenting rice, and causing mucormycosis in humans (Walther & al. 2013).

Geographic distribution—Australia, Belgium, Brazil, China, Finland, France, Germany, Greece, India, Japan, South Africa, Spain, the Netherlands, New Zealand, Turkey, Ukraine, Vietnam.

Comments—Recently, in a taxonomic review based on a polyphasic approach of *M. circinelloides* complex, Wagner & al. (2019) reclassified previously described forms into distinct species: *M. circinelloides*, *M. griseocyanus*, *M. jansseni*, and *M. lusitanicus*. Our isolate corresponds well to the morphological characters described and illustrated by Van Tieghem (1875) and Schipper (1976). This is the first report of *M. circinelloides* in the Brazilian upland forest.

Mucor griseocyanus Hagem, Skr. Videnskr.-Selsk. Christiania, Kl. I, Math.-Natur. 1907(7): 28 (1908) Fig. 2a–d

Colony: initially white to yellowish gray, then becoming dark gray, reverse yellowish, colonizing the entire Petri dish (9 cm diam., 0.5–1.5 cm high) in 5 days, at 25°C, on MEA. Sporangiophores hyaline to light gray, sympodially branched, with long or short branches; short branches often recurved, 6–10(–15) µm diam., with incrusted walls. Sporangia at first yellowish then becoming brown to brownish dark, globose, 20–65(–75) µm diam., with smooth or slightly incrusted and deliquescent wall, leaving a small but evident collar. Columellae grey to brownish grey, obovoid in larger sporangia, 25–60(–65) × 20–55 µm, and globose in the smallest ones, 20–45(–65) µm diam., smooth-walled. Sporangiospores hyaline, ellipsoid to broadly ellipsoid, 4–10 × 3.5–6.5 µm, globose to subglobose, 3.5–8 µm diam., smooth-walled. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 9.VII.2016, C.A.F. Souza (URM 7771).

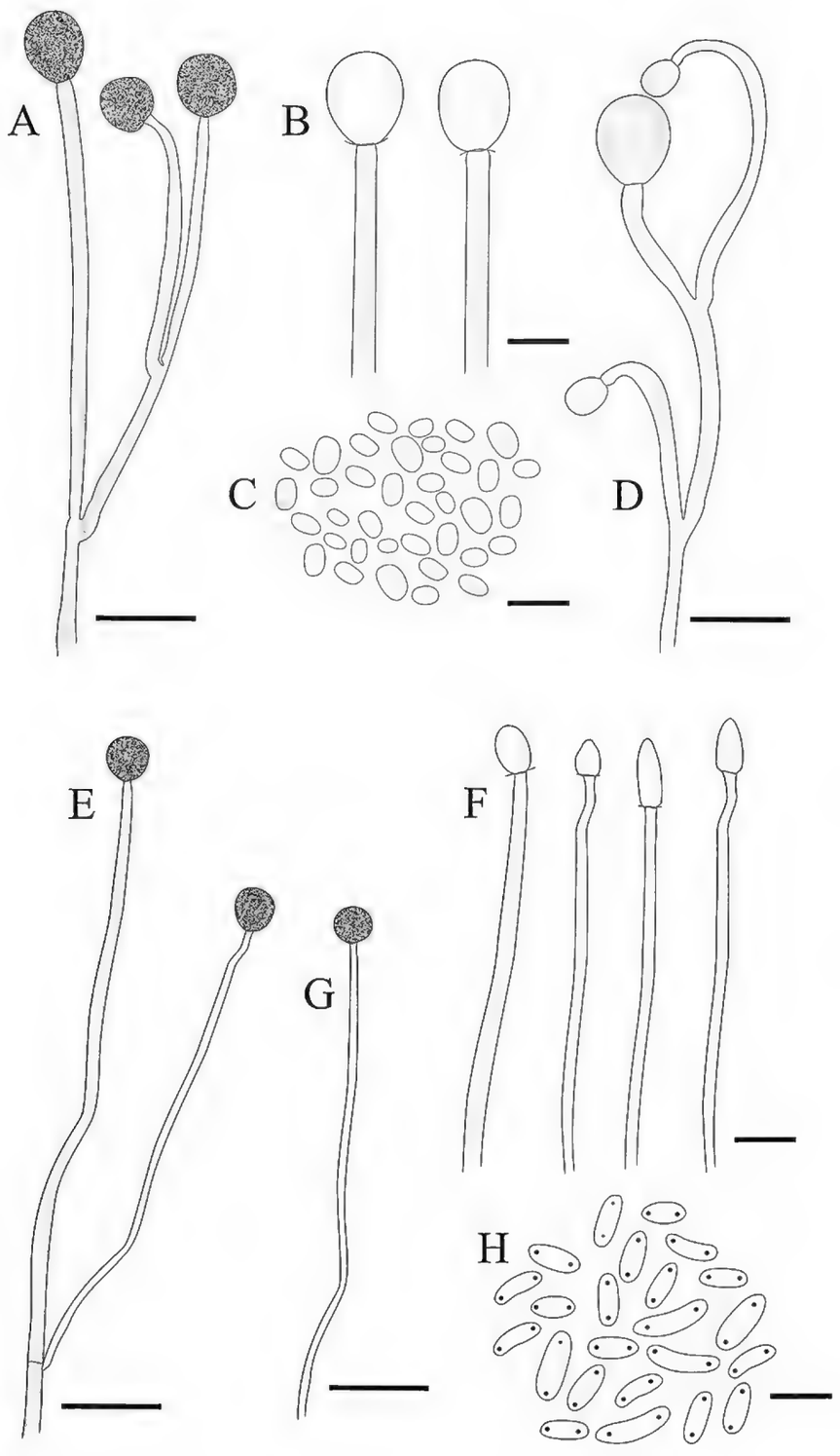

Fig. 2. ***Mucor griseocyanus*** (URM 7771): A. Sympodially branched sporangiophore with sporangia; B. Unbranched sporangiophores with columellae; C. Ellipsoid to broadly ellipsoid sporangiospores; D. Sympodially branched sporangiophore with columellae. ***Mucor guilliermondii*** (URM 7868): E. Simple branched sporangiophore with sporangia; F. Unbranched sporangiophores with columellae; G. Unbranched sporangiophore with sporangium; H. Ellipsoid and cylindrical to reniform sporangiospores. Scale bars = 20 µm.

Habitat—Forest soil, leaf litter, *Zea mays*, milk powder, canned strawberries (Schipper 1976), and excrements of cattle, goat, and sheep (Souza & al. 2017).

Geographic distribution—Brazil, Germany, India, Norway, South Africa, the Netherlands.

Comments—*Mucor griseocyanus*, previously described as a forma of the *M. circinelloides* complex (Schipper 1976) but recently reclassified by Wagner & al. (2019), is characterized by the production of globose sporangia ≤60 µm diam., sympodially branched sporangiophores, and ellipsoid sporangiospores. The characters of our isolate URM 7771 are similar to those described by Schipper (1976) except for its larger sporangial and columellar diameters. Schipper (1976) also noted such variations (≤60 µm diam. in the sporangia and ≤38 × 55 µm in the columellae). This is the first record of *M. griseocyanus* in the Brazilian upland forest.

Mucor guilliermondii Nadson & Philippov,
Rev. Gén. Bot. 37: 450 (1925) Fig. 2E–H

Colony white to slightly light gray, reverse yellowish, low and exhibiting slow growth (6 cm diam., ≤3 mm high) after 6 days, at 25°C frequently recurved, rarely presenting lateral branches, smooth-walled. Sporangia hyaline to yellowish, globose or subglobose to slightly depressed, 14–60 µm diam., smooth-walled, deliquescent, with vitreous aspect. Columellae hyaline, elongated-conical, infrequently subglobose and ellipsoidal, 15–30 × 5.5–14.5 µm, with slightly incrusted wall; a small collar may occur. Sporangiospores hyaline, ellipsoid and cylindrical to reniform, some irregular in shape, 3.5–8 × 2–4.5 µm, with one or more droplets at each end, smooth-walled. Chlamydospores globose to subglobose, cylindrical, and doliiform. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 9.VIII.2016, C.A.F. Souza (URM 7868).

Habitat—Soil (Schipper 1978, Nadson & Philippov 1925) and excrements of tapir (*Tapirus terrestris*; Santiago & al. 2008).

Geographic distribution—Belgium, Brazil, France, Malaysia, Russia.

Comments—The characteristics of the *M. guilliermondii* strain URM 7868 are closely similar to the descriptions of Nadson & Philippov (1925) and Schipper (1978). Moreover, the URM 7868 characters correspond well to the description and illustration of Santiago & al. (2008), who isolated this species from tapir dung in an Atlantic Forest area in Recife, Pernambuco, Brazil, except for sporangiophore width, which was slightly smaller (≤6 µm diam.)

than those described in our study. Our isolate represents the first record of *M. guilliermondii* in the soil of the Brazilian upland forest.

Mucor hiemalis Wehmer, Ann. Mycol. 1(1): 39 (1903) FIG. 3A–E

COLONY initially white becoming light yellow, reverse yellowish, exhibiting good growth (9 cm diam., ≤1.5 cm high) after 4 days, at 25°C, on MEA. SPORANGIOPHORES hyaline, with or without yellowish contents, simple, monopodially or slightly sympodially (not frequent) branched with long branches, 8–17 µm diam., smooth-walled. SPORANGIA firstly hyaline to yellowish then turning dark yellow, globose to slightly depressed, 20–70(–80) µm diam., wall smooth and deliquescent. COLUMELLAE hyaline, ellipsoid with truncate base, globose when young, 15–40(–50) × 20–45 µm, hyaline to grayish, smooth-walled. SPORANGIOSPORES hyaline, ellipsoid, some flattened on one side, 2.5–8.5 × 2–5.5(–7.5) µm. OIDIA globose to subglobose and doliiform. CHLAMYDOSPORES present in the aerial mycelium. ZYGOSPORANGIA not observed.

SPECIMEN EXAMINED—**BRAZIL, PERNAMBUCO, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 9.VIII.2016, C.A.F. Souza (URM 7881).

HABITAT—Different soil types (Schipper 1976; Trufem 1978, 1981a; Lima & al. 2016, 2018a; Anand & al. 2018), excrement of cattle, goat, and sheep (Souza & al. 2017), water samples (Alananbeh & al. 2017), *Picea abies* litter (Haňáčková & al. 2015), fresh biofilms from submerged rocks (Hoque & Fritscher 2017), commercial cheese (Ando & al. 2012), processed products derived from maize (e.g., maize flour, corn meal, cooked cornflakes; Santiago & Souza-Motta 2008), humans (Abirami 2019), endophytic in tuberous rhizome of *Curculigo orchioides* (Gaikwad & al. 2017) causing the disease *Miscanthus* rhizome rot (Beccari & al. 2010), and in mandarin fruit (Satio & al. 2016).

GEOGRAPHIC DISTRIBUTION—Australia, Austria, Bolivia, Brazil, Canada, Colombia, China, Denmark, Estonia, France, Germany, India, Japan, Malaysia, New Zealand, Nigeria, Northern Ireland, Norway, Russia, South Africa, Spain, Sweden, Switzerland, Ukraine, the Netherlands, United Kingdom, United States.

COMMENTS—*Mucor hiemalis* has a wide distribution in Brazilian ecosystems, being reported in the Atlantic Forest, Caatinga, and Cerrado domains (Schoenlein-Crusius & al. 2006, Souza & al. 2017, Lima & al. 2018b). URM 7881 shows a close similarity to the descriptions of Schipper (1973) and Lima

& al. (2018b), although differences in columellar size were observed between our isolate and those reported by Schipper (1973; ≤38 × 30 µm) and Lima & al. (2018b; ≤40 × 30 µm). This is the first report of *M. hiemalis* in the Brazilian upland forest.

Mucor inaequisporus Dade, Trans. Br. Mycol. Soc. 21(1–2): 25 (1937) FIG. 3F–I

COLONY intensely yellow, reverse yellow, mostly at the point of inoculum, exhibiting rapid growth (9 cm diam., ≤10 mm high) after 3 days, at 25°C, on MEA. SPORANGIOPHORES brownish, 9–30 µm diam., simple or with long and short sympodial branches (3–10 times), mostly in older colonies, erect, undulating, slightly curved, exhibiting one or several randomly spaced septa, with or without yellowish contents. SPORANGIA initially yellow, then becoming brown, globose and subglobose to slightly depressed, 70–130(–180) × 60–120 µm diam.; sporangial wall mostly deliquescent, but persistent in the smaller sporangia. COLUMELLAE hyaline to brownish yellow, varied in shape, often pyriform, conical or oblong, ellipsoid, obovoid and subglobose, 60–100 × 45–80(–120) µm, smooth-walled; collar commonly observed. SPORANGIOSPORES variable in shape and size, hyaline, with granular contents, mostly ellipsoid, sometimes flattened at one side, 5–15 × 3.5–10 µm, globose and subglobose, 8–15 µm diam., some irregular in shape, 25 × 15 µm. RHIZOIDS present, short to long, and poorly branched. CHLAMYDOSPORES and ZYGOSPORANGIA not observed.

SPECIMEN EXAMINED—**BRAZIL, PERNAMBUCO, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, 1056 m a.s.l., soil samples, 5.X.2016, C.A.F. Souza (URM 7871).

HABITAT—Isolated from fruits of *Artocarpus glaucus, Bouea macrophylla, Diospyros kaki, Flacourtia inermis, Musa ×paradisiaca, Spondias mombin, Syzygium cumini,* and *Theobroma cacao* (Dade 1937, Boedijn 1959, Santiago & al. 2013b) and from rhizosphere of root-knot nematode host plants (Zangeneh & al. 2007).

GEOGRAPHIC DISTRIBUTION—Brazil, Ghana, Indonesia, Iran, Malaysia.

COMMENTS—*Mucor inaequisporus* was first described by Dade (1937) from *S. mombin* fruits in Aburi, Ghana. This species is characterized by the highly variable form and size of columellae and sporangiospores (Schipper 1978). Our isolate shows similarities to those described by Schipper (1978) and Santiago & al. (2013b), although the sporangiophores with irregular swellings as described by Santiago & al. (2013b) were not observed in URM 7871. In addition, the columellae described by Dade (1937) and Schipper (1978) are

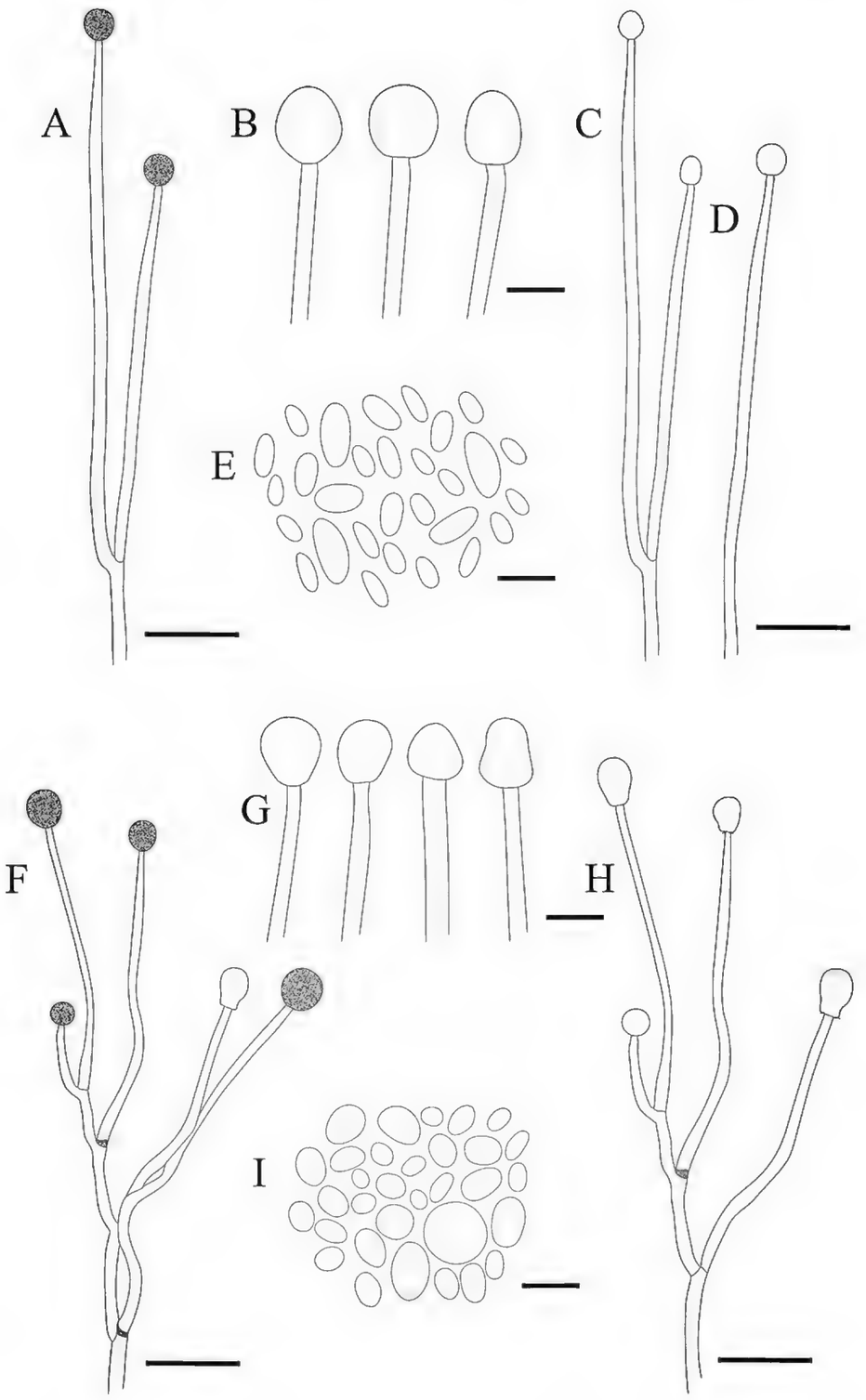

Fig. 3. ***Mucor hiemalis*** (URM 7881): A. Simple branched sporangiophore with sporangia; B. Unbranched sporangiophores with columellae; C. Simple branched sporangiophore with columellae; D. Unbranched sporangiophore with columella; E. Sporangiospores ellipsoid, some flattened at one side. ***Mucor inaequisporus*** (URM 7871): F. Sympodially branched sporangiophore with sporangia and columella; G. Unbranched sporangiophore with columellae; H. Sympodially branched sporangiophore with columellae; I. Sporangiospores variable in shape and size. Scale bars = 20 μm.

smaller (≤83 µm diam.) than those of URM 7871. According to Schipper (1978), different strains of *M. inaequisporus* can exhibit morphophysiological variations. This is the first report of *M. inaequisporus* in the Brazilian upland forest.

Mucor indicus Lendn.,
Bull. Soc. Bot. Genève, sér. 2, 21: 258 (1930 ["1929"]) Fig. 4a–d

Colony initially white, becoming deep yellowish, with yellowish reverse, colonizing the entire Petri dish (9 cm diam., 1 cm high) in 4 days, at 28°C, on MEA. Sporangiophores hyaline to yellowish, erect, sympodially branched, with long branches, rarely circinate, 5–12(–15) µm diam., smooth-walled. Sporangia brownish, globose to subglobose, 32–45(–50) µm diam., with diffluent wall. Columellae grayish or yellowish brown, globose 30–50 µm diam., subglobose, 27–30 × 42–45(–50) µm or applanate, 20–22 × 27–30(–32) µm, smooth-walled; collar small and infrequent. Sporangiospores hyaline, smooth-walled, often ellipsoid, 4–6 × 3–6 µm and subglobose, 4–6(–7.5) µm diam. Chlamydospores and Oidia present. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, 1056 m a.s.l, soil samples, 5.X.2016, C.A.F. Souza (URM 7854).

Habitat—Different soil types (Lendner 1930, Szwedek-Trzaska & Glowacka 2011), fermented products of grains like ragi (Lee & Fujio 1999), goat dung (Souza & al. 2016), and humans (Álvarez & al. 2011).

Geographic distribution—Brazil, Germany, India, Indonesia, Poland, Qatar, South Africa, Spain, Switzerland, United States, Vietnam.

Comments—The morphological characteristics of *M. indicus* strain URM 7854 agree with the descriptions by Schipper (1978) and Souza & al. (2016). Specimens of *M. indicus* are characterized by the production of sporangiophores repeatedly sympodially branched, with long branches and sporangiospores often ellipsoid and subglobose. The ellipsoid sporangiospores of URM 7854 were larger than those reported by Schipper (1978: ≤5.7 × 4.4 µm). This is the first report of *M. indicus* in the Brazilian upland forest.

Mucor irregularis Stchigel, Cano, Guarro & E. Álvarez,
Medical Mycol. 49(1): 71 (2011) Fig. 4e–h

Colony initially white then turning yellowish to cream-colored, reverse yellowish, with cottony aspect, colonizing the entire Petri dish (9 cm diam., 1 cm high) after 4 days, at 25°C, on MEA. Sporangiophores hyaline,

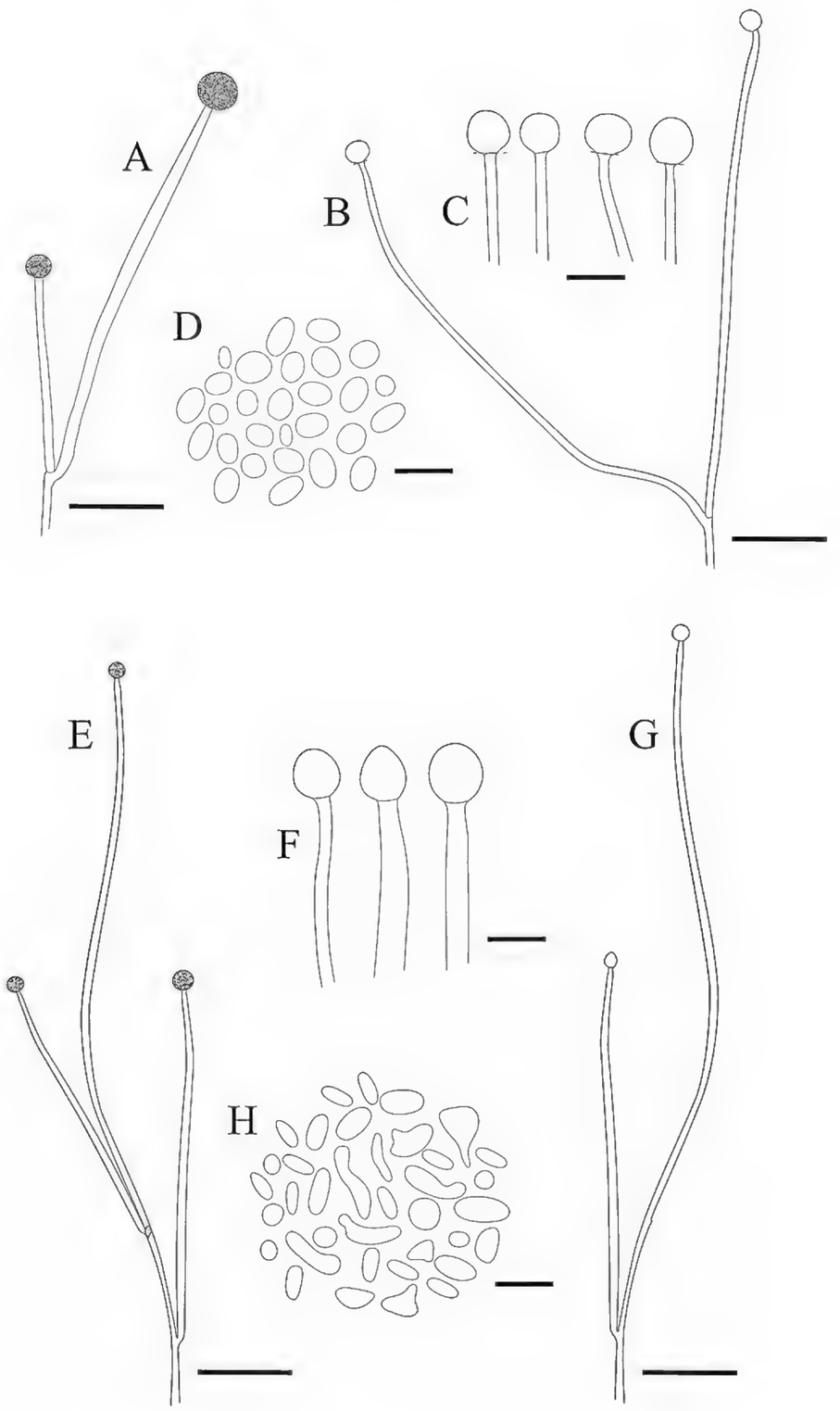

Fig. 4. ***Mucor indicus*** (URM 7854): A. Simple branched sporangiophore with sporangia; B. Simple branched sporangiophore with columellae; C. Unbranched sporangiophores with columellae; D. Ellipsoid and subglobose sporangiospores. ***Mucor irregularis*** (URM 7773): E. Sympodially branched sporangiophore with sporangia; F. Unbranched sporangiophores with columellae; G. Simple branched sporangiophore with columellae; H. Sporangiospores variable in shape and size. Scale bars = 20 μm.

with or without yellowish contents, erect, sympodially and monopodially branched, arising from aerial hyphae 5–15.5(–25) µm diam., smooth-walled. Sporangia grayish brown, globose to subglobose, 30–40(–50) µm diam., with diffluent wall. Columellae brownish, globose, 12–30 µm diam., ellipsoid to cylindrical, 30–35 × 20–30 µm and rarely conical, 25–40 × 20–35 µm, some variable in shape, smooth-walled; collar small and little evident. Sporangiospores hyaline, mostly ellipsoid 2.5–10 × 2–5(–10) µm, subspherical to ovoid 4–9.5 × 2.5–7 µm, or globose, 2.5–10 µm diam., some irregularly shaped ≤12 µm diam., smooth-walled. Rhizoids hyaline, slightly branched. Chlamydospores and oidia observed. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, 1056 m a.s.l., soil samples, 5.X.2016, C.A.F. Souza (URM 7773).

Habitat—Humans, causing human primary cutaneous mucormycosis (Zheng & Chen 1991, Lu & al. 2013), soldier fly larvae gut (Nguyen & al. 2016), and soil (Lima & al. 2018d). One specimen has been reported as endophytic in the roots of *Sorghum bicolor* (Lima & al. 2018d).

Geographic distribution—Australia, Brazil, China, Japan, India, Nigeria, South Korea, United States.

Comments—*Mucor irregularis* was first isolated and described as *Rhizomucor variabilis* R.Y. Zheng & G.Q. Chen from lesions of a patient, causing cutaneous or subcutaneous clinical infections (Zheng & Chen 1991). The holotype was described as producing variable and irregular shaped columellae. Although our isolate corresponded well with the description of the holotype, we did not observe any variable and irregular columellae. Lima & al. (2018d), who isolated *M. irregularis* from soil in Brazil, also reported no irregularly shaped columellae.

Mucor jansseni Lendn.,
Bull. Herb. Boissier, sér. 2, 7: 251 (1907), [as '*janseni*'] Fig. 5a–d

Colony initially white to light grayish then turning dark gray, growing in the entire Petri dish (9 cm diam., 0.5–1.5 cm high) in 5 days, reverse yellowish gray, at 25°C, on MEA. Sporangiophores hyaline to grayish, short branches repeatedly sympodially branched, rarely monopodially branched later, apical branches often short and circinate, 7–10(–20) µm diam., with or without yellowish contents; wall slightly incrusted. Sporangia initially yellowish then dark brownish, globose and subglobose 20–80(–90) µm diam.,

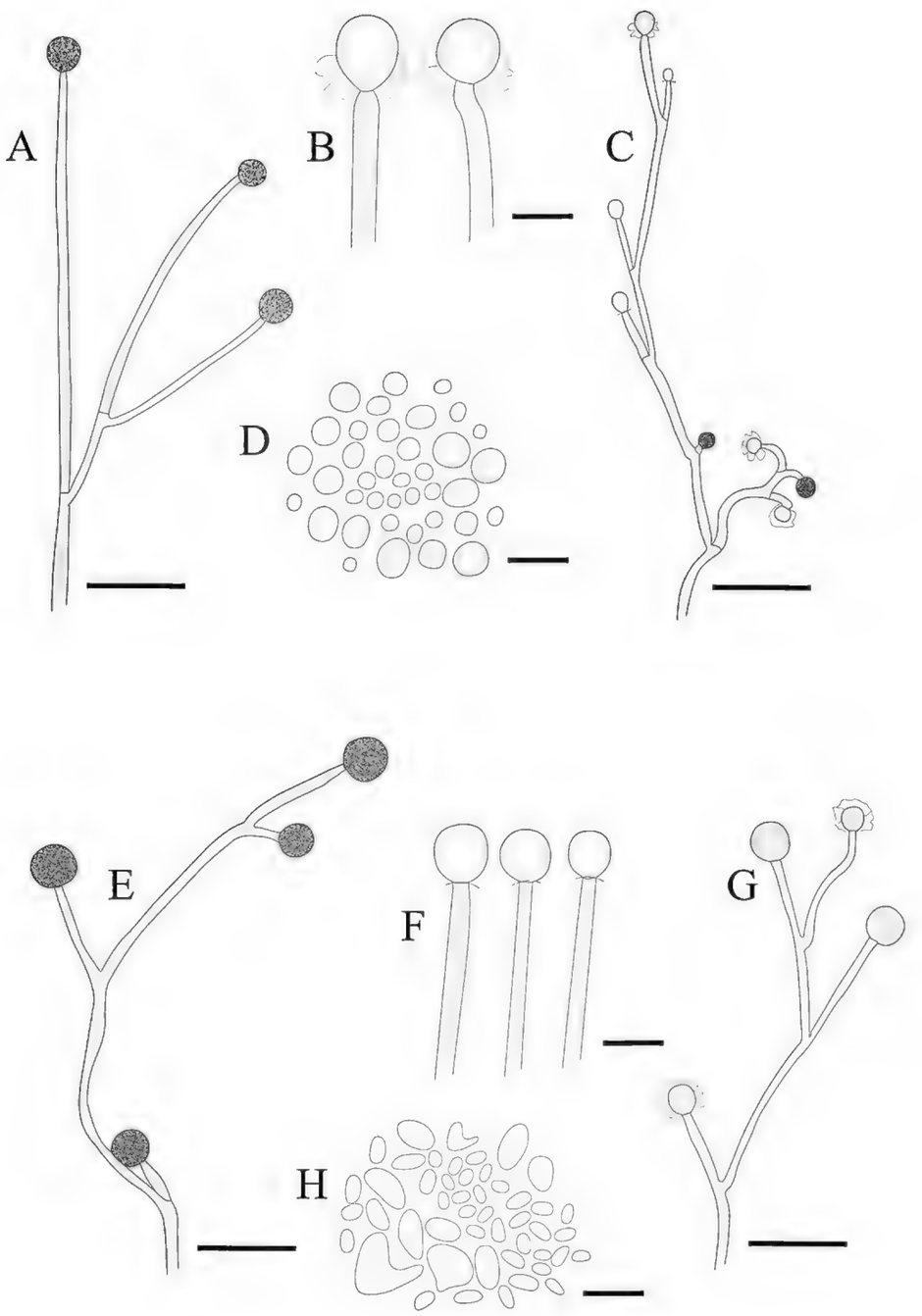

FIG. 5. ***Mucor jansseni*** (URM 7880): A. Sympodially branched sporangiophore with sporangia; B. Unbranched sporangiophore with columellae; C. Repeatedly sympodially branched sporangiophore with columellae and sporangia; D. Globose to subglobose sporangiospores. ***Mucor lusitanicus*** (URM 7853): E. Sympodially branched sporangiophore with sporangia; F. Unbranched sporangiophores with columellae; G. Sympodially branched sporangiophore with columellae; H. Sporangiospores variable in shape and size. Scale bars = 20 µm.

with incrusted wall, which is persistent in the small sporangia. Columellae grayish, obovoid in the larger sporangia, 25–65 × 20–50 µm, and globose in the smaller ones, 10–55(–65) µm diam., smooth-walled; collar common. Sporangiospores hyaline, globose to subglobose 3–10 µm diam.; smooth-walled. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 5.VII.2016, C.A.F. Souza (URM 7880).

Habitat—Forest and grassland soils (Schipper 1976), excrements of cattle, goats, and sheep (Souza & al. 2017), the insect *Carausius morosus* (Schipper & al. 1975), and humans (Walther & al. 2013).

Geographic distribution—Brazil, China, France, India, Malaysia, Russia, South Africa, South Korea, the Netherlands, Vietnam.

Comments—*Mucor jansseni* was previously described as a forma in the *M. circinelloides* complex, recently reclassified by Wagner & al. (2019). The morphological characteristics of URM 7880 show close similarity to the description of Schipper (1976) (as *M. circinelloides* f. *jansseni*). Sporangia and columellae of URM 7880 were larger than those reported by Schipper (1976: sporangia ≤80 µm diam.; columellae ≤35 × 33 µm).

Mucor lusitanicus Bruderl.,
Bull. Soc. Bot. Genève, sér. 8: 276 (1916) Fig. 5e–h

Colony grayish yellow to brownish, reverse yellow, colonizing the entire Petri dish (9 cm diam., ≤1 cm high) after 5 days at 25°C on MEA. Sporangiophores hyaline to slightly pale gray, with or without yellowish contents, 6–20 µm diam., repeatedly sympodially branched, wall slightly incrusted. Circinate branches are uncommon. Sporangia initially yellowish then becoming brownish, globose to subglobose, 18–75(–85) µm diam., sporangial wall deliquescent. Columellae grayish, globose and subglobose, 15–55(–75) µm diam., smooth-walled; collar common. Sporangiospores hyaline, variable in size and shape, ellipsoid, 3–7 × 2.5–3.5 µm, irregular, 4–14 × 3–12 µm, rarely globose to subglobose, 2.5–5 µm diam., smooth-walled. Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, 1056 m a.s.l., soil samples, 4.IX.2016, C.A.F. Souza (URM 7853).

Habitat—Isolated from forest soil and *Zea mays* (Schipper 1976, Walther & al. 2013), fermented soybeans (sufu starter: Schipper 1976; meju: Hong & al.

2012), excrements of cattle and sheep (Souza & al. 2017), humans (Álvarez & al. 2011).

Geographic distribution—Brazil, China, France, Mexico, Portugal, Russia, South Africa, United States.

Comments—*Mucor lusitanicus* was previously described as a forma of the *M. circinelloides* complex, recently reclassified by Wagner & al. (2019). This species is characterized by producing variably sized and shaped sporangiospores, with some irregularity in shape. The morphological characteristics of *M. lusitanicus* of URM 7853 agree with those described by description of Schipper (1976) except that its irregular sporangiospores are smaller than those reported by Schipper (1976: 5.5 × 17.6 µm) and its ellipsoid sporangiospores are larger than those observed by Alves & al. (2002: ≤2.5 × 3.1 µm).

Mucor luteus Linnem. ex Wrzosek, Mycotaxon 111: 81 (2010) Fig. 6a–d

Colony with cottony aspect, warm buff-colored, reverse yellowish, exhibiting good growth (9 cm diam., ≤1.5 cm high) after 4 days at 25°C on MEA. Sporangiophores hyaline, with or without yellowish contents, 5–16 µm diam., simple or slightly branched sympodially, smooth-walled. Sporangia hyaline to yellowish, globose, 15–70(–90) µm diam., wall smooth and deliquescent. Columellae hyaline to grayish, globose, 12.5–60 µm diam., smooth-walled; collar often evident. Sporangiospores hyaline, narrow ellipsoidal to fusiform, 2.5–10 × 1.5–5 µm, smooth-walled. Chlamydospores and Zygosporangia not observed.

Specimen examined—**BRAZIL, Pernambuco, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 5.IX.2016, C.A.F. Souza (URM 7772).

Habitat—Isolated from different soil types (Santiago & al. 2013a, Sarsaiya & al. 2017), rhizoplane of grapevine *Vitis labrusca* (Lima & al. 2014), excrements of cattle, goat, and sheep (Souza & al. 2017), water samples (Zvereva & al. 2012), oral and cloacal openings of free-living four-lined snakes *Elaphe quatuorlineata* (Lukač & al. 2017), and as endophytes of chili crops (*Capsicum annuum* L.; Trizelia & al. 2017).

Geographic distribution—Australia, Brazil, Germany, India, Japan, Montenegro, Nigeria, Russia, South Africa, Sweden, and Poland.

Comments—The morphological characteristics of *M. luteus* described here are closely similar to the description in Schipper (1973). Sporangiospores narrow

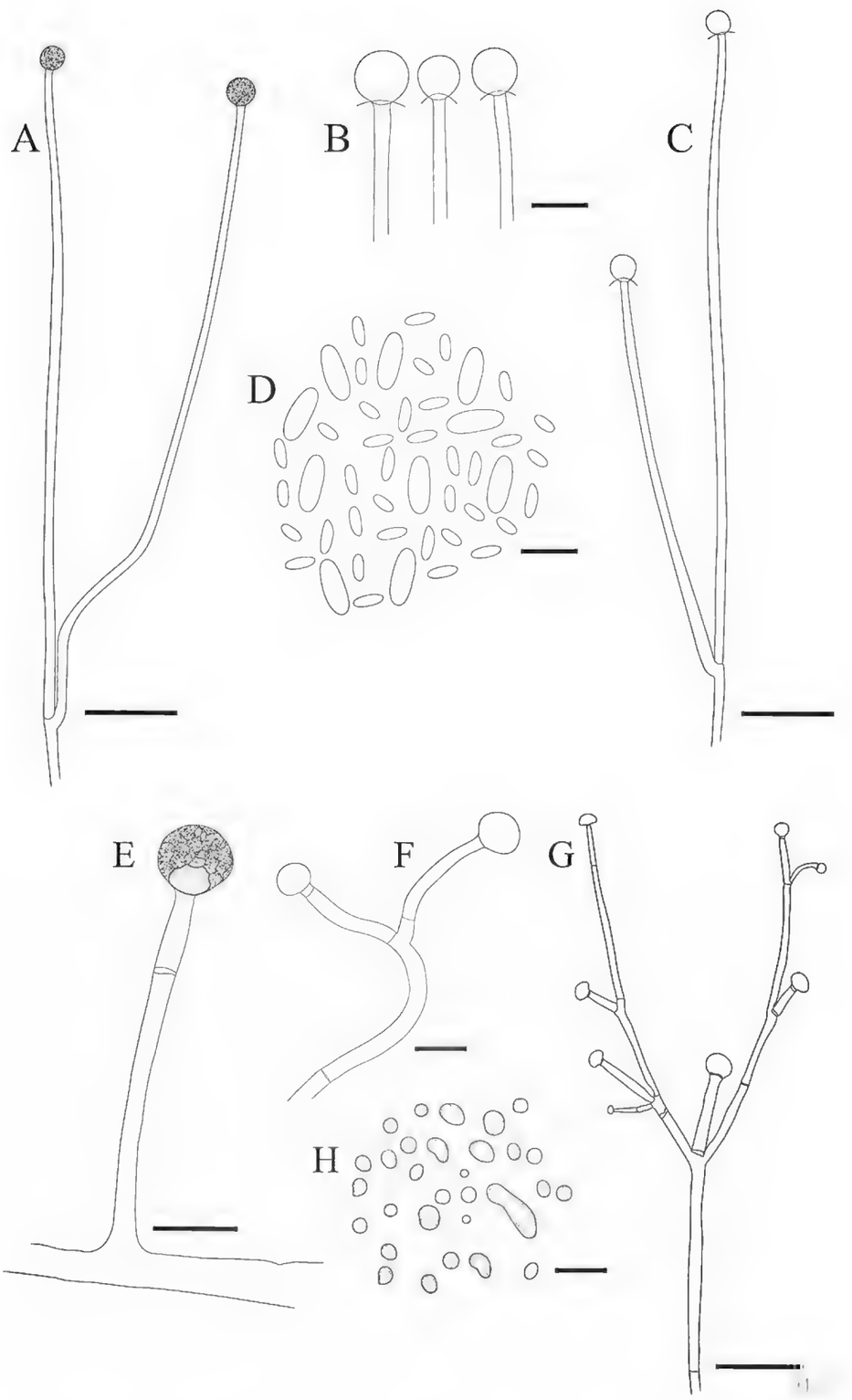

Fig. 6. ***Mucor luteus*** (URM 7772): A. Simple branched sporangiophore with sporangia; B. Unbranched sporangiophores with columellae; C. Simple branched sporangiophore with columellae; D. Narrow ellipsoidal to fusiform sporangiospores. ***Mucor septatiphorus*** (URM 7364 - holotype): E. Unbranched septate sporangiophore with sporangium; F. Branched multiseptate sporangiophore with columellae; G. Sympodially branched multiseptate sporangiophore with columellae; H. Sporangiospores variable in shape and size. Scale bars = 20 μm.

ellipsoidal to fusiform correspond to those described by this author, although small differences in the maximum sizes of sporangia and columellae were observed in our strain. Schipper (1973) reported sporangia ≤70 µm diam. as well as columellae ≤45 × 47 µm, both smaller than those of URM 7772.

Mucor septatiphorus C.A.F. Souza, T.R. Cordeiro & A.L. Santiago, **nom. nov.**

FIG. 6E–H

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≡ *Mucor septatus* C.A.F. Souza, T.R. Cordeiro & A.L. Santiago, Phytotaxa 351(1): 56 (2018), [as "*septatum*"], nom. illeg., non Bezold 1889.

SPECIMEN EXAMINED—**BRAZIL, PERNAMBUCO, Brejo da Madre de Deus**, brejo da Serra do Bituri, 8.1833°S 36.4000°W, 1008 m a.s.l., soil samples, 5.IX.2016, C.A.F. Souza (URM 7364, holotype).

HABITAT—Isolated from the soil (Souza & al. 2018).

GEOGRAPHIC DISTRIBUTION—Brazil.

COMMENTS—This species is characterized by the concomitant presence of bent, circinate, simple or branched (most heavily branched) sporangiophores with one to several septa. The description and illustration of the holotype (URM 7364) are provided by Souza & al. (2018).

Mucor souzae C.A.F. Souza, D.X. Lima & A.L. Santiago, Persoonia 40: 307 (2018) FIG. 7A–D

SPECIMEN EXAMINED—**BRAZIL PERNAMBUCO, Triunfo**, Brejo do Sítio Carro Quebrado, 7.8748°S 38.1034°W, 913 m a.s.l., soil samples, 6.XI.2016, C.A.F. Souza (URM 7553, holotype).

HABITAT—Isolated from the soil (Crous & al. 2018).

GEOGRAPHIC DISTRIBUTION—Brazil.

COMMENTS—*Mucor souzae* is mainly characterized by producing sporangiophores from aerial mycelia, simple or repeatedly sympodially branched, with long or short branches as well as variably shaped and sized sporangiospores. One or two septa sometimes form below the sporangia. The description and illustration of the holotype (URM 7553) are available in Crous & al. (2018).

Mucor variicolumellatus L. Wagner & Walther. Persoonia 44: 92 (2019) FIG. 7E–H

SPECIMEN EXAMINED—**BRAZIL, PERNAMBUCO, Taquaritinga do Norte**, Brejo de Taquaritinga do Norte, 7.9078°S 36.0403°W, 1056 m a.s.l., soil samples, 5.X.2016, C.A.F. Souza (URM 7769).

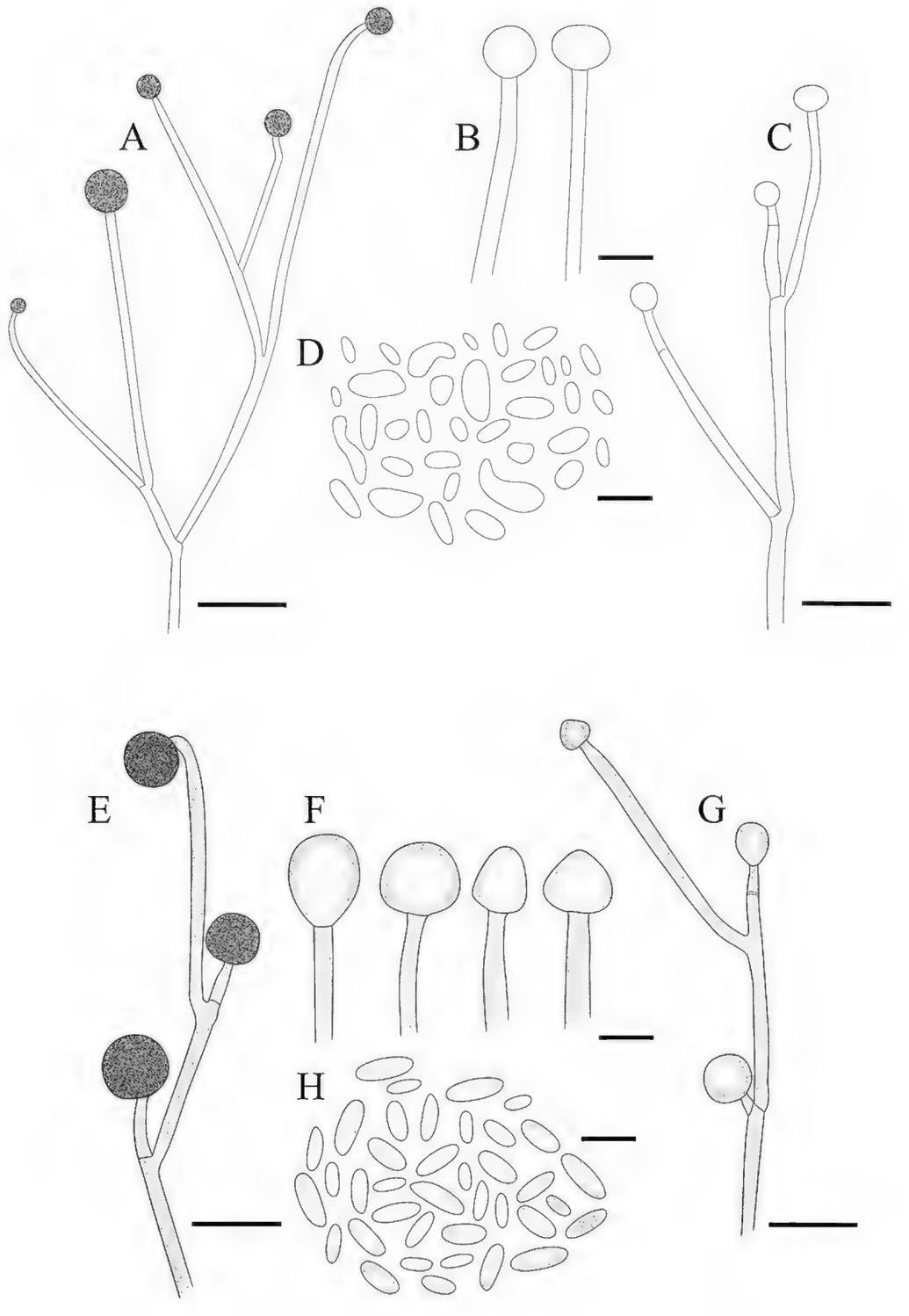

Fig. 7. ***Mucor souzae*** (URM 7553, holotype): A. Sympodially branched sporangiophore with sporangia; B. Unbranched sporangiophores with columellae; C. Sympodially branched sporangiophore with columellae; D. Sporangiospores variable in shape and size. ***Mucor variicolumellatus*** (URM 7769): E. Sympodially branched sporangiophore with sporangia; F. Unbranched sporangiophores with columellae; G. Sympodially branched sporangiophore with columellae; H. Sporangiospores ellipsoidal, variable in size. Scale bars = 20 μm.

Habitat—Isolated from *Tremella*, maize meal, humans (Álvarez & al. 2011, as *M. fragilis*), and soil (Souza & al. 2020).

Geographic distribution—Brazil, Germany, Malawi, United States.

Comments—*Mucor variicolumellatus* was proposed by Wagner & al. (2019). It was isolated from humans (Álvarez & al. 2011, as *M. fragilis*) and maize meal from Malawi. This species resembles *M. lusitanicus,* except that only *M. variicolumellatus* produces obovoid, ovoid, and strawberry-shaped columellae. The morphological characteristics of *M. variicolumellatus* illustrated here show a close similarity to the description given by Wagner & al. (2019). A detailed description and illustration of URM 7769 are available in Souza & al. (2020).

Discussion

Studies on *Mucoromycota* (including *Mucor* spp.) in Brazilian ecosystems are fragmented. Around 110 taxa of this phylum were registered in Brazil, mostly concentrated in the Atlantic Forest (66 taxa), Caatinga (27), and Cerrado (16) domains (Lima & al. 2016, 2018b; Souza & al. 2018; Flora e Funga do Brasil 2022). To date, only seven *Mucor* species have been reported in the Brazilian upland forests, including three new species isolated from the soil in this ecosystem (Lima & al. 2018c, Souza & al. 2018, Crous & al. 2018).

Hawksworth & Lücking (2017) estimated that there are between 2.2 to 3.8 million species of existing fungi; nevertheless, currently, only around 120,000 are known. Thus, it is probable that the species richness in tropical areas is underestimated, and new studies may reveal a greater richness of *Mucoromycota* in these areas. The authors highlighted the number of undescribed species waiting to be discovered in biodiversity hot spots in the tropics.

In our study, 14 *Mucor* species were isolated from upland forests, of which twelve are presented here as new records for this poorly studied ecosystem. Brazilian upland forest areas have undergone a continuous and systematic degradation process in an unsustainable and intense manner (Medeiros & Cestaro 2019), with serious impacts on the quality of original ecosystems (Freire & al. 2018). Therefore, studies on the knowledge of fungi diversity in this ecosystem are crucial to generate data for the ecological maintenance of these areas and to guide conservation efforts for these fungi.

The results presented here underscore the richness of *Mucor* species in three upland forest fragments and the data allow for expanding the taxonomic knowledge and the geographical distribution of these fungi. The

isolated specimens were deposited at the URM culture collection of the Federal University of Pernambuco, for further tests in biochemical studies on the evaluation of enzyme production, such as amylases, proteases, cellulases, and tannases for industrial application.

Acknowledgments

We would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for the for the scholarship granted to the first author, and the National Council for Scientific and Technological Development (CNPq) for the research scholarship granted to André Luiz Santiago and Erika Medeiros. This research is financed by the project 'Diversity of *Mucoromycotina* in the different ecosystems of the Atlantic Rainforest of Pernambuco' [FACEPE (First Projects Program PPP/FACEPE/CNPq, APQ 0842-2.12/14)]. We also thank Drs. Maria Helena Alves (Universidade Federal do Delta do Parnaíba, Brazil), Jadson D. P. Bezerra (Universidade Federal de Goiás, Brazil), and Nomenclature Editor Shaun Pennycook for the critical revisions of the manuscript.

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